Reliability of IGBTs in solid-state pulsed power supplies for CO_2 TEA lasers

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The IGBT (insulated gate bipolar transistor) is a modern solid-state switch with wide applications in power electronics. Little information is, however, available on the performance and reliability of the switch in pulsed power supplies. Results of reliability tests conducted on a high-power, high-voltage IGBT are presented with special focus on applications in high-voltage laser pulsed power supplies. It was found that the IGBT could be reliably used in pulsed power supplies where the peak switching current exceeded the average current rating up to five times. Furthermore, the IGBT could be reliably connected in series to increase the switch operating voltage.

Introduction

Although many pulsed power supplies for CO_2 TEA lasers and excimer lasers still make use of thyratrons, there has been a strong drive to replace the older thyratron switches with modern solid-state devices, which have important advantages over thyratrons. These include longer service lifetime, low cost and greater availability. One type of solid-state switch available on the market today is the IGBT (insulated gate bipolar transistor). These devices are voltage-controlled transistors and allow for better control of the switching process compared to thyratrons and thyristors, that is, IGBTs can be easily turned on and off. On the other hand, thyratrons are robust and have the advantage of being able to switch high voltages and high currents directly, tolerating high over-voltages and over-currents, whereas solid-state switches are limited to comparatively low voltages and in general are more sensitive to over-voltages, over-currents and electromagnetic interference. In addition, the performance of IGBTs is normally specified for switch mode power supplies, which have different operating conditions from pulsed power supplies. Consequently, there is little information available on the reliability of modern solid-state switches such as the IGBT in pulsed power supplies.

Operating conditions

The typical topology of a pulsed power supply for excitation of gas discharge lasers such as CO_2 TEA and excimer lasers is shown in Fig. 1. It consists of a primary switching unit, where the initial high-voltage pulse is generated, and a pulse compression and conditioning unit. The primary switching unit contains an active switching element (e.g. spark gap, thyratron or solid-state switch), which generates the initial pulse. Because of the limited voltage rating of solid-state switches, the primary switching unit may also contain a pulse transformer in order to step-up the pulse voltage to the required level. In most cases the pulse is generated too slowly for the direct excitation of a gas laser. In order to reduce the rise-time of the voltage pulse to a value suitable for the generation of stable laser discharges, the generated pulse has to be compressed by a magnetic pulse compression (MPC) unit.[1]

The initial pulse has to be generated as fast as possible in order to reduce the size and cost of the MPC unit. This can lead to very high peak switching currents, because during the pulse all the pulse energy has to pass through the switch. However, the duty cycle of current pulses is very small, since the time between successive pulses is generally much longer than the pulse duration. Consequently, peak switching currents in laser pulsed power supplies are orders of magnitude higher than the average switching current. From an economic viewpoint, it would be advantageous if IGBTs could be used to switch current pulses with a peak current of several times the average current rating of the device. Unfortunately, IGBTs are not designed for this type of operation and currently are mostly designed for and used in switch mode power supplies where the average and peak switching currents are the same order of magnitude. It is therefore important to determine the reliability of IGBTs under operating conditions encountered in pulsed power supplies.

The IGBT that was tested was a high-power, high-voltage module (Semikron, type SKM300GB174D) containing two separate IGBTs. Each IGBT can handle a peak voltage of 1700 V and an average current of 300 A. The IGBT is intended to be used in a pulsed power supply for a mini CO_2 TEA laser excited with an input energy of 5 J at repetition rates up to 600 Hz. The required excitation pulse has a peak voltage of between 25 kV and 28 kV with a rise-time of approximately 100 ns. The resulting operating parameters of the IGBT are summarised in Table 1. The switched current pulse is shown in Fig. 2, which under normal operating conditions is a single sinusoidal pulse. It is important to note that the peak switching current is between four and five times the rated average current of the IGBT.

IGBT peak pulse current rating and failure mechanisms

The largest limiting factor in the peak pulse current rating of an IGBT is the maximum saturated switching (collector) current. Any switching current that exceeds the maximum saturated switching current will be clamped, forcing the IGBT into a saturated state where it acts as a current limiter. The voltage over the IGBT will then increase to counteract any further rise in the switching current, i.e. the IGBT effectively turns off. The high collector current and increased IGBT voltage will cause very large instantaneous power dissipation inside the device, which can induce damaging thermal stresses. In general, the limit on the switching current of high-power, high-voltage IGBTs is between four and six times the rated current of the device.

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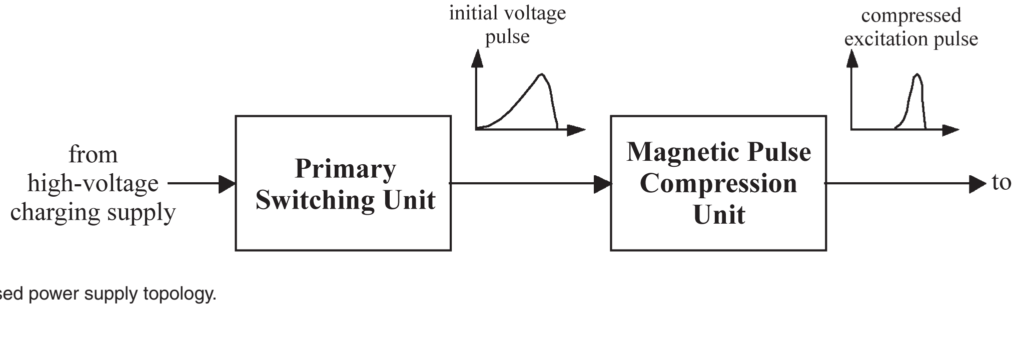

Fig. 1. Laser pulsed power supply topology.

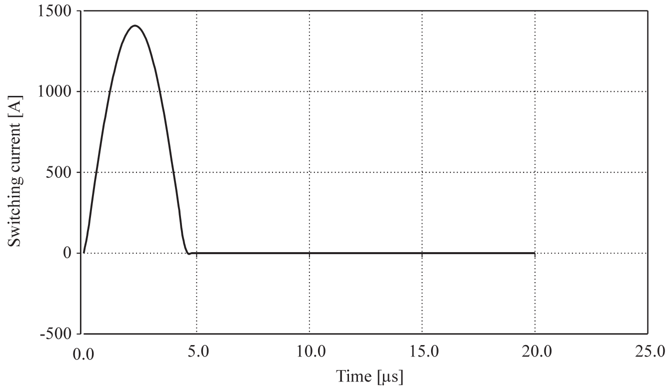

Fig. 2. Profile of a switched current pulse.

The limitation on the peak switching current due to thermal considerations is normally less severe and rather has an effect on the lifetime of the IGBT. The short current pulses switched by the IGBT can induce very fast rises in the junction temperature. This leads to large temperature gradients inside the silicone wafer and between structural layers of the IGBT, causing large and potentially damaging thermal stresses. The thermal stresses can furthermore propagate the formation and growth of cracks inside the silicone wafer,[2] thereby degrading the device and reducing its lifetime. The formation and growth of cracks inside the IGBT is difficult to predict and it is important to conduct lifetime tests to determine whether a specific IGBT is suitable for the target application.

Reliability tests

Lifetime tests were performed on the SKM300GB174D IGBT. For this, the IGBT was repeatedly switched and submitted to similar conditions as encountered in laser pulsed power supplies. The test setup for the purpose is shown in Fig. 3. A RLC circuit was used as a dummy pulser to simulate similar switching conditions as in the laser pulsed power supply. This was achieved by selecting appropriate values for the RLC components generating switching current pulses with a peak current of 1400 A and a pulse duration of 4.45 μs as shown in Fig. 2. The IGBT's electrical and thermal characteristics were monitored during the lifetime test period. Changes in these properties can give an indication of whether the switching conditions induce gradual degradation in the device before complete failure. The IGBT was tested for a total of 0.5×10^9 switching cycles at a switching rate of 300 Hz.

The thermal resistance R_{thjc} of the IGBT recorded over the test period is shown in Fig. 4. It was initially measured to be 0.068 K/W, which is close to the value of 0.07 K/W specified by the manufacturer. After the first 100×10^6 switching cycles, the thermal resistance dropped by approximately 15% to between 0.057 and 0.058 K/W. Thereafter, it stayed constant within the measurement accuracy. This is an indication that no measurable degradation in the thermal characteristics of the IGBT was detected. The thermal resistance also remained constant for the test period, from 400×10^6 to 500×10^6 switching cycles, when the peak pulse current was increased to 1500 A, which was 100 A above the peak current used in the final pulsed power supply. The initial drop in thermal resistance was probably caused by the heat-conducting paste inside the IGBT module that settles after the device had been heated internally by switching and conduction losses during the first period of operation.[4]

Furthermore, no change was observed in the electrical performance of the IGBT, which therefore survived 0.5×10^9 switching cycles without showing any signs of degradation

Table 1. Typical operating parameters of an IGBT in a commercial laser pulsed power supply for a mini CO_2 TEA laser.

Peak switching current, $I_{p,peak}$	1405 A
Switched voltage, V_o	2430 V
Pulse transfer time (pulse duration), τ	4.3 μs
Pulse energy	4.65 J

Reliability under fault conditions

To determine the reliability of the switch when operating in the laser power supply, the effect of circuit malfunctions and load fault conditions on the switch have to be investigated. Under fault conditions, the pulse energy is not, or is only partially, dissipated in the load, leading to circuit oscillations and subjecting the switch to large forward or reverse voltages and currents. In order to prevent device failure under these conditions, protection circuits have to be incorporated. The following fault conditions may occur in a laser pulsed power supply:

- *Flashover*: flashovers are true circuit failures, which should not occur and are caused by insufficient electrical insulation or device failure. Flashovers can be approximated as low-impedance connections that occur between the two points of a flashover. Critical points in the pulsed power supply are the MPC unit and the pulse transformer secondary. Breakdown of the electrical insulation leads to destructive flashovers and necessitates the replacement of the damaged component.
- *No laser discharge*: the laser fails to discharge when the excitation voltage is below the breakdown voltage of the gas medium or the laser is operated with an unsuitable gas mixture. With the absence of a laser discharge the load represents an open circuit and no energy can be deposited into the laser medium. Consequently, most of the pulse energy remains in the pulsed power supply and is reflected back to the primary switching unit.
- *Laser arcing*: unstable discharges between the laser electrodes can result in arc formation. There are many causes of unstable discharges[3] and this type of fault condition is the most common. Although arcing discharges can have a much lower impedance than typical stable discharges, a large portion of the pulse energy is dissipated in the arc, thereby significantly reducing the energy remaining in the pulsed power supply.

Flashovers have highly non-linear characteristics, which can cause unpredictable circuit behaviour and are also difficult to simulate. In general, flashovers cause unwanted electrical

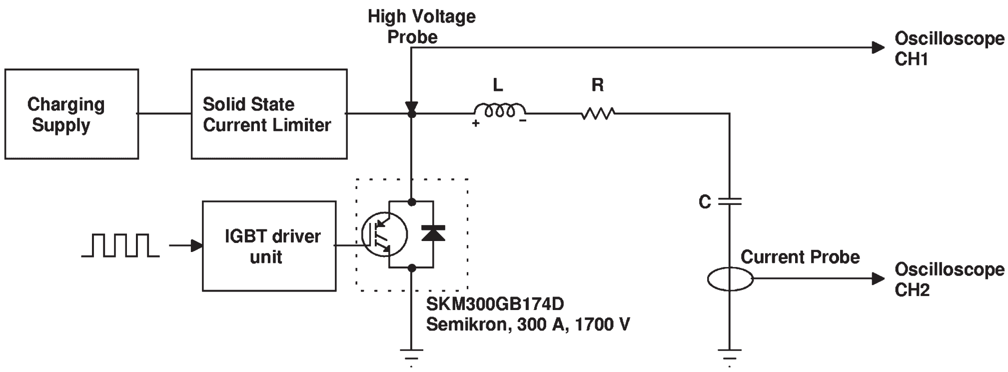

Fig. 3. Setup for a lifetime test.

oscillations in the pulsed power supply, which can lead to catastrophic failure or reduced lifetime of the IGBT. As a result of the unpredictable nature of flashovers, it is highly advisable to avoid them by careful design and construction and by using adequate high-voltage insulation.

Laser fault conditions, i.e. laser arcing and absence of laser discharges, on the other hand, are not easily preventable and can occur frequently. Owing to the fault condition not all the pulse energy can be deposited into the laser medium and a portion of the energy remains in the pulsed power supply, causing unwanted electrical oscillations. The switching current shown in Fig. 5 obtained for the case when the laser failed to discharge illustrates this effect. Initially, the normal switching current pulse (see Fig. 2) can be observed. This was followed by oscillations caused by the fault condition, i.e. the absence of a laser discharge. Note that the oscillations are weakly damped and can last much longer than the switched current pulses obtained under normal operation. These oscillations, due to the absence of a laser discharge, can again lead to a reduction of the IGBT's lifetime or even to immediate failure.

Laser arcing is less severe than the absence of a laser discharge. It was found that, in general, laser arcing does not reduce the lifetime of the IGBT significantly. However, since the lifetime of the IGBT is greatly reduced when the laser fails to discharge, additional lifetime tests were performed under this condition. The SKM300GB174D unit was subjected to oscillating switching currents as shown in Fig. 5. The results of these tests are presented in Table 2. Without a protection circuit (snubber), the IGBT had a lifetime of only approximately 10^5 switching cycles. With protection circuits the lifetime could be extended to more than 25×10^6 switching cycles. It is important to note that even with protection circuits the lifetime is greatly reduced when the laser fails to discharge. It is therefore necessary to add additional failsafe circuits that will shut the laser down under a laser fault condition.

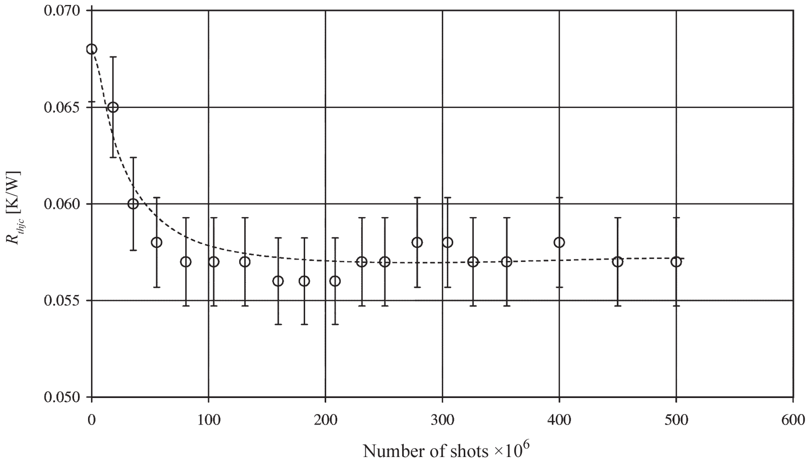

Fig. 4. Thermal resistance of the IGBT during the lifetime test period.

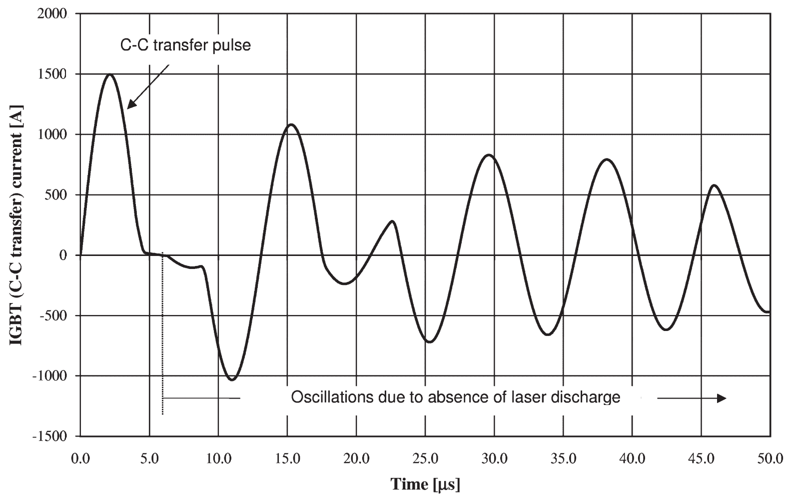

Fig. 5. IGBT switching current under a laser fault condition (laser fails to discharge).

Increasing the switch voltage

It is advantageous to stack IGBTs in series in order to increase the total switch operating voltage. Increased switching voltages will result in smaller transfer peak currents for the same pulse energy. Hence, less expensive IGBTs with lower current ratings can be used. Automatic voltage sharing between the IGBTs connected in series can be obtained as long as the switching time of the IGBTs is at least an order of magnitude faster than the pulse duration.[5]

Conclusion

The experimental IGBT survived 0.5×10^9 switching cycles at peak currents of up to five times the average current rating without showing any signs of degradation. While this is satisfactory for a preliminary test, it is not possible to build reliable statistics from tests conducted on a single subject. It will therefore be necessary to perform more extensive tests, where several devices are investigated for at least 10^9 shots. Nonetheless, these results demonstrate that IGBTs can be reliably used in pulsed power supplies where the peak switching current exceeds the average current rating up to five times.

Furthermore, it was found that while laser arcing did not influence switch lifetime significantly, flashovers and the absence of laser discharges affected the lifetime adversely, making the implementation of IGBT protection and additional failsafe circuits necessary. These shut down the laser under discharge fault conditions, so preventing IGBT failure.

The switch operating voltage could be increased and associated switched peak currents reduced by connecting the IGBTs in series. However, to ensure voltage sharing, the IGBT switching time must be significantly faster (at least by an order of magnitude) than the pulse duration.

Table 2. IGBT lifetimes under prevailing laser fault condition (laser fails to discharge).

IGBT no.	Protection circuit (snubber)	Number of shots	Failure
1	No	100 000	Short-circuit
2	Over-voltage	25 000 000	Short-circuit
3	Over-voltage	36 000 000	Short-circuit

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